The FIRST radio survey: The $K-z$ diagram of FIRST radio sources identified in the Boötes and Cetus fields

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This paper presents the Hubble diagram ($K-z$ relation) for FIRST (Faint Images of the Radio Sky at 20 cm) radio sources identified in the Boötes and Cetus fields. The correlation between the K magnitude of the FIRST-NDWFS sample and the photometric redshifts found to be linear. The dispersion about the best fit line is given by 1.53 for the whole sample and 0.75 at $z > 1$. The paper also presents a composite $K-z$ diagram of FIRST radio sources and low-frequency selected radio samples with progressively fainter flux-density limits (3CRR, 6C, 7CRS and the EIS-NVSS sample). The majority of FIRST radio sources lie fainter than the no evolution curve ($3\,L_{\star}$ galaxies) probably highlighting the fact that the galaxy luminosity is correlated with the radio power.

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1 Introduction

Powerful radio sources have played a crucial role in our understanding of galaxy evolution. The host galaxies of powerful radio sources, such as radio galaxies and quasars, are identified with giant elliptical (Best et al. 1998, Mclure & Dunlop 2000, Jarvis et al. 2001, De Breuck et al. 2002, Willott et al. 2003, Zirm et al. 2004) and are associated with the most massive black holes (Taylor et al. 1996, Dunlop et al. 2003, Mclure et al. 2004, Mclure & Jarvis 2004) in the universe. Studies of these objects at high redshift have shown a tight correlation in the Hubble $K-z$ diagram for powerful radio sources. The infrared *K*-magnitude against redshift relation has been widely used as a tool for investigating the evolution with cosmic epoch of stellar populations of luminous galaxies, since K corrections, dust extinction corrections, and the effect of any secondary star formation are all relatively unimportant at near infrared wavelengths. It has played an important infrared role in the search for and the study of high redshift galaxies (e.g Lilly & Longair 1984, Eales et al. 1987). For example, the first radio galaxy discovered at $z > 3$ was selected on the basis of a faint $K \sim 18.5$ magnitude (Lilly 1988). The Hubble $K-z$ diagram is known to be an excellent tool to measure stellar masses of galaxies up to higher redshift (Eales et al. 1999, van Breugel et al. 1998, Lacy et al. 2000) and has been widely used to study the evolution in radio galaxies.

Lilly & Longair (1984) showed for the 3CRR sample that the $K-z$ relation is well defined with approximately constant dispersion to redshifts $z > 1$ and indicates evolution in the galaxies'luminosity of about a magnitude at $z \sim 1$ if $\Omega_0 = 1$. They concluded that the giant elliptical hosting the low redshift ($z < 0.6$) radio galaxies from the 3CRR sample are the result of passively evolving stellar populations which formed at high redshift (e.g Lilly 1989). Subsequent studies based on low frequency selected radio samples with successively fainter flux-density limits have been subject to a degeneracy between radio luminosity and redshift (see e.g.; 6CE sample which is 5 times fainter than the 3CRR sample (Eales et al. 1997), 7CIII, 7C, 20 times fainter than 3CRR sample (e.g. Lacy et al. 2000; Willott et al. 2003)).

Willott et al. (2003) have investigated the $K-z$ relation for 205 radio galaxies with high spectroscopic completeness ($z \sim 0.05-4.4$) obtained from a combined data set selected at different flux limits; 3CRR (Laing, Riley & Longair 1983), 6CE (Eales et al. 1997, Rawlings, Eales & Lacy 2001), 6$C^{\star}$ (Jarvis et al 2001a,b) and the 7CRS (Lacy et al. 2000, Willott et al. 2003) showing that 3CRR and 7CRS radio galaxies offset by ~ 0.55 in the *K*-magnitudes over all redshift while the 6C differ from the 3CRR ones by ~ 0.3 mag. These results have been interpreted as a correlation of both properties with black whole mass (Willott et al. 2003, McLure et al. 2004). The best fit for the combined sample (3CRR, 6C[1], 7CRS) quoted by Willott et al. (2003) is: $K(z) = 17.37 + 4.53\,\log_{10} z - 0.31\,(\log_{10} z)^2$. The brightest sample is 3CRR selected at 178 MHz with a flux density limit of $S_{178} \geq 10.9$ Jy, the intermediate samples are the 6CE and 6C* selected at 151 MHz with flux density limits of $2.0 \leq S_{151} \leq 3.93$ Jy and $0.96 \leq S_{151} \leq 2.00$ Jy respectively. The 7CRS selected at 151 MHz with flux density limits of $S_{151} \geq 0.5$ Jy.

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[1] The 6C sample refers to the 6CE and the 6C*samples

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In order to overcome the drawbacks of using the most powerful radio galaxies, and flux-limited samples, it is important to select samples that cover a wide range of flux-density limits and redshift. This was one of the primary motivation for developing a combined EIS-NVSS radio sample which is 12 times fainter than 7CRS survey (CENSORS: Best et al 2003). Brookes et al. 2006 established a $K-z$ relation for their radio galaxies of the CENSORS and used it to calculate redshift for non spectroscopically identified sources in their sample (Brookes et al. 2008). The EIS-NVSS sample (Brookes et al. 2006) has been selected at 1.4 GHz with flux density limit of 7 mJy.

In EL Bouchefry (2008a), the author defined the FIRST-Boötes/Cetus radio sample and presented robust optical /infrared counterparts to FIRST radio sources. Based on the multi-wavelength (*Bw R I J K*), photometric redshift has been calculated using the public code *Hyperz*. In EL Bouchefry (2008b), the optical/infrared properties of FIRST radio sources identified in Boötes/Cetus fields and their host environment is discussed. This paper shed light on the $K-z$ relation of the FIRST radio sources identified in the Boötes and the Cetus fields ($33^\circ \leq \delta \leq 36^\circ$, $216^\circ < \alpha \leq 221^\circ$). These data are combined with those from the 3CRR, 6CE (Rawlings et al. 2001) 6C* (Jarvis et al. 2001a,b) and 7C-III (Lacy et al. 2000) and EIS-NVSS (Brookes et al. 2006) to define the $K-z$ relation over 400 radio galaxies ranging from 1Jy to 1 mJy levels. Section 2 describes the radio and optical data. Section 3 presents the Hubble diagram of the FIRST-Boötes/Cetus radio sample, and conclusions are summarised in section 4.

Throughout this paper it is assumed that $H_\circ = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ unless stated otherwise.

2 The sample data

2.1 The NDWFS survey

The NOAO Deep Wide Field Survey (NDWFS) is a deep multi-band imaging (*Bw, R, I, J, H, K*) designed to study the formation and evolution of large scale structures (Jannuzi et al. 1999; Brown et al. 2003). This survey consists of two fields[2]; the first one is located in the Boötes field centred on approximately $\alpha = 14^h\ 30^{'}\ 05.7120^{"}$, $\delta = +34^\circ 16^{'} 47.496^{"}$, covering a 3 by 3 square degrees region, and the latter one is located in a 2.3 by 4 square degrees region in the Cetus field. The survey catalogue has been split by declination range into four strips ($32^\circ \leq \delta < 33^\circ, 33^\circ \leq \delta < 34^\circ, 34^\circ \leq \delta < 35^\circ, 35^\circ \leq \delta < 36^\circ$); each strip observed in four bands (*Bw, R, I, K*). Only the last two strips has been considered in a previous study of FIRST radio sources in the Boötes field (EL Bouchefry & Cress 2007). The magnitude limits are: $Bw \sim 25.5$ mag, $R \sim 25.8$ mag, $I \sim 25.5$ mag and $K \sim 19.4$ mag.

[2] http://www.noao.edu/noao/noaodeep/

2.2 The FLAMINGOS survey

FLAMEX (Elston et al. 2006) is a wide area, deep near infrared imaging survey that covers 7.1 square degrees within the NDWFS survey regions; 4.7 square degrees in the Boötes field and 2.4 square degrees in the Cetus field in both *J* and *K* filters. The FLAMEX catalogue is publicly available [3]. This survey has been used to get infrared data for the second strip ($33^\circ \leq \delta < 34^\circ$) of the Boötes field.

2.3 The FIRST catalogue

The radio data are from the 2002 version of the FIRST (Faint Images of the Radio Sky at Twenty-Centimetres; Becker et al 1995) Very Large Array catalogue[4], and it is derived from 1993 through 2002 observations. The FIRST radio survey has been carried out in recent years with the VLA in its B-configuration to produce a map of 20 cm (1.4 GHz) sky with a beam size of 5.4 arcsec and an rms sensitivity of about 0.15 mJy/beam. The 2002 version of the catalogue covers a total of about 9033 square degrees of the sky (8422 square degrees in the north Galactic cap and 611 square degrees in the south Galactic cap); and contains 811,117 sources from the north and south Galactic caps. The accuracy of the radio position depends on the brightness and size of the source and the noise in the map. Point sources at the detection limit of the catalogue have positions accurate to better than 1 arcsec at 90% confidence; 2 mJy point sources typically have positions good to 0.5 arcsec. The radio surface density is $\sim 90\ \mathrm{deg}^{-2}$. About 900 sources fall within the Boötes field and ~ 242 radio sources fall within the Cetus field.

3 The Hubble diagram

The total number of FIRST radio sources identified in the Boötes field is 688/900 radio sources (either in one or more bands). There are 338 (48%) FIRST radio sources optically identified in K band, and 273 (39%) were identified in four bands. In Cetus field, there are 113/242 (47%) counterparts to FIRST radio sources in J band, 124/242 (51%) candidates in K band. For a simple morphological classification, I used the Source Extractor stellarity parameter S/G (Bertin & Arnouts 1996) provided by the NDWFS catalogue. The Sextractor parameter has values between 0 (galaxy, more to the point, non-star) and 1 (for point-like sources; QSOs or stars). All the sources with $\mathrm{S/G} < 0.7$ were classified as galaxies and sources with $\mathrm{S/G} > 0.7$ were classified as point-like objects (QSOs or stars). The classification yielded 235 (34%) radio sources classified as galaxy (identified in four bands) and 33 (5%) radio sources classified as point-like objects. For sources identified in K band, 261 (37%) were classified as galaxies and 77 (11 %) as point-like objects. The point-like objects tend to have a blue

[3] http://flamingos.astro.ufl.edu/extragalactic/overview.html

[4] The FIRST catalogue is available online at http://sundog.stsci.edu

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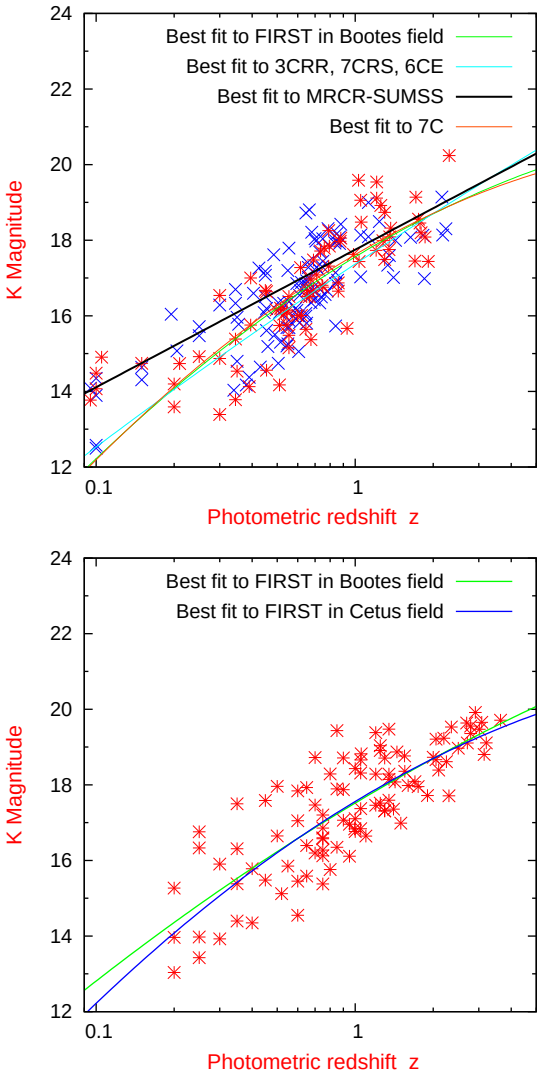

Fig. 1 *top panel*: *K* band magnitude against redshift for all FIRST radio sources identified in Boötes field. Crosses denote sources identified in the range $34^\circ \leq \delta < 36^\circ$ (introduced in EL Bouchefry & cress 2007) and stars indicate the new counterparts of FIRST radio sources in the second strip ($33^\circ \leq \delta < 34^\circ$). The lines show the best fitting relationship between *K* magnitude and $\log_{10}(z)$ for different samples. *lower panel*: *K* band magnitude against redshift for all FIRST radio sources identified in Cetus field.

colour which is consistent with those of QSOs, so they are likely QSOs. A total number of 22 sources that were classified as point-like sources are spectroscopically identified in the SDSS and were confirmed to be QSOs.

3.1 The $K-z$ diagram for FIRST radio sources

In order to investigate the $K-z$ relation for the FIRST-Boötes/Cetus radio sample, I used the best photometric redshift estimates with $\chi^2 < 2.7$ ($\%90$ confidence) for all FIRST radio sources identified in *Bw, R, I, K* (Boötes field) and *I, J* (Cetus field). The point-like sources were excluded from the $K-z$ analysis due to the fact that the $K-z$ relation is applicable only to radio galaxies for which the K band emission is dominated by an old elliptical galaxy.

The $K-z$ relation for the new counterparts of FIRST radio sources in the second strip ($33^\circ \leq \delta < 34^\circ$) augmented with those introduced in EL Bouchefry & Cress 2007, in Boötes field, represented by stars and crosses respectively, is shown in Figure 1 (top panel). The green line is the best fit second order polynomial relationship between the *K* band and $\log_{10}\ z$ for all the data (in Boötes field):

$$K(z) = 17.56 + 4.14\ \log_{10}\ z - 1.20\ (\log_{10}\ z)^2, \quad (1)$$

the cyan line is the best fit of the combined sample of 3CRR, 6C and 7CRS (Willott et al. 2003), the black line illustrates the best fit of Bryant et al. (2009), and the red line shows the best fit for the 7CRS sample alone. Brookes et al. (2006) claim that this latter is similar to the fit they obtained for the CENSORS survey. Compared to the best fit of Willott et al. (2003), the fit for the FIRST radio sources is shifted slightly to fainter magnitude ($\sim\ 0.15\,\mathrm{mag}$) which could support finding that brighter radio sources are associated with galaxies that are brighter in *K* band, even for faint radio sources. More complete and deeper sample is required to investigate this further. A subsample of FIRST radio sources with flux-densities greater than 10 mJy is considered but found no better fit to the Willott et al. (2003) relation.

Figure 1 (lower panel) displays the *K* band magnitude of FIRST radio sources against photometric redshift obtained for sources identified in Cetus field. The blue line in the figure shows the best fitting to the $K-z$ relation for FIRST in Cetus field. The best fitting to the $K-z$ relation (in Cetus field) is:

$$K(z) = 17.52 + 4.09\ \log_{10}\ z - 0.62\ (\log_{10}\ z)^2, \quad (2)$$

and the best fit for all the data (Boötes and Cetus field) is:

$$K(z) = 17.50 + 4.13\ \log_{10}\ z - 0.30\ (\log_{10}\ z)^2. \quad (3)$$

Recently, Bryant et al. (2009) have compiled a sample of 234 ultra-steep spectrum (USS) selected radio sources in order to find high redshifts sources. These authors have spectroscopic information for only 36 sources (15%). Bryant et al. (2009) have investigated the $K-z$ diagram and quoted three fits (see Table 1). Their fit to the $K-z$ relation was found to be fainter than the Willott et al. (2003) by more than 0.3 magnitudes at all redshifts. However, complete sample, deep infrared data and spectroscopic information are required in order to well understand the $K-z$ relation as this diagram has been widely used to calculate redshift in the absence of spectroscopic information.

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3.2 Dispersion in the $K-z$ relation

The increase in the dispersion about the $K-z$ relation has been used to study the evolution of the stellar population in powerful galaxies, and to probe the formation epoch of radio galaxies. For example, Eales et al. (1997) have concluded that the radio galaxies are in the formation epoch at $z=2$ based on their study to the sample B2/6C, while at $z<2$ the radio galaxies are passively evolving. They found that the dispersion in the $K-z$ relation at high redshifts ($z>2$) of the B2/6C sample is 2.7 times greater at low redshift ($z<2$). Using the 7CIII sample, Lacy et al. (2000) found similar effect. Jarvis et al. (2002), found no evidence of an increase in the dispersion, and concluded that most radio galaxies have formed their stars at $z>2.5$ and passively evolved since then based on their study to the 6C sample. Willott et al. (2003) also found no increase in the dispersion about the $K-z$ relation in agreement with Jarvis et al. (2001). Bryant et al. (2009), have also calculated the dispersion about the best-fit to $K-z$ relation as a function of redshift. These authors found a standard deviation $\sigma=0.7$ that is approximately constant at all redshifts (see their table 4), supporting the results found by Jarvis et al. (2001) and Willott et al. (2003) that radio galaxies hosts have been evolving passively since epochs corresponding to $z=3$ or earlier. In this study, the dispersion about the mean $K-z$ relation is given by $\sigma_K=1.53$. Similar correlation is found in other bands (*Bw*, *R* and *I*) but with a larger scatter. One notes that the scatter in *K* band is smaller at high redshift ($\sigma_K=0.76$ at $z>1$), than at lower redshift, consistent with the idea that fainter radio survey probably include fainter galaxies that are different from the typical galaxies associated with bright radio sources. For the combined 3CRR, 7CRS, 6C data of Willott et al. (2003), $\sigma=0.58$ at redshifts up to $z=3$. A reason for the increased spread at lower radio luminosities is that a wider range of galaxy masses host these radio sources. This could be related to the different radio emission mechanisms (most FIRST radio sources have FRI luminosities, where as most of the 3CRR, 6C, 7CRS sample are FRII radio sources). Owen & Laing (1989) found that FRIs reside in hosts which on average 0.5 magnitudes brighter than those of FRII of comparable radio luminosity. Perhaps FRIs also have a broader spread in host luminosity. But the question is how much the photometric redshift errors contribute to the increased scatter in the $K-z$ relation. It is well known that the accuracy of photometric redshift increases with the number of bands used to calculate redshift (especially infrared bands). Here, only sources identified in four or five bands were considered for the $K-z$ relation (in order to get accurate photometric redshifts). The total number of sources identified in four bands is governed by the lower fraction of sources identified in *K* band, which means only bright sources were included, and there could be a considerable number of sources fainter ($K>20$) than the magnitude limit of the *K* band data. With the additional criterion of $\chi^2<2.7$ (90% confidence limit) one excludes sources with a not very good fit and this makes the sample even more incomplete. These issues could also contribute to the flatness of the $K-z$ slope and the large scatter in the $K-z$ relation.

One should also note that, the Boötes and Cetus samples are not complete. As mentioned earlier, the Boötes field is split by declination into four strips; $32^\circ<\delta\leq 33^\circ$, $33^\circ<\delta\leq 34^\circ$, $34^\circ<\delta\leq 35^\circ$, $35^\circ<\delta\leq 36^\circ$. No infrared data is availabe for the first strip, and the other strips are partially covered in K band. Moreover, the K band catalogue is not as deep as the *Bw*, *R* and *I* catalogues. There is only a fraction of sources identified in K band compared to the other bands. The Boötes and Cetus K band magnitude histograms drop of at 19.5 mag. Therefore, the lack of $K>20$ could cause several effects:

1. The slope of the $K-z$ relation for FIRST radio is a little bit flatter than for the combined sample 3CRR, 6C, 7CRS.

2. There could be a significant number of K band faint radio galaxies missing (due to the incompleteness of the optical survey), and because of this most of the sources will lie at the bright end of K band. Therefore, the observed FIRST $K-z$ relation having a very small offset from the combined sample 3CRR, 6C, 7CRS of 0.15 mag at $z=1$ could be misleading and in reality there could be a larger difference in magnitudes between the samples.

In Figure 2, the three upper curves show non evolving and passive evolution $1\,L_\star$ galaxies as a function of redshift. The passive evolution models (blue and green plots) assume the stars in the galaxies formed at $z=5$ and $z=10$ respectively. The three lower curves illustrate passive stellar evolution tracks of a $3\,L_\star$ (K) galaxy for an instantaneous burst of star formation and one in which the burst of star-formation lasts 1 Gyr at $z=5$, as well as a no evolution curve as derived by Jarvis et al. (2001). The model curves in Figure 3 show non evolving and passive evolution $3\,L_\star$. As clearly seen from the plots, the majority of the FIRST radio sources lie fainter than the no evolution curve ($3\,L_\star$ galaxies). This could be due to the fact that the FIRST survey is deeper than the low-frequency complete samples that were used to make the $K-z$ diagrams in Jarvis et al. (2001) and in Willott et al. (2003); probably highlighting a correlation between the galaxy luminosity and the radio power (Willott et al. 2003; McLure et al. 2004).

Figure 3 shows the near infrared Hubble diagram of *K* magnitude versus redshift z for the FIRST-Boötes/Cetus sample combined with data of four samples compiled from the literature: 3CRR, 6CE, 6C*, and EIS-NVSS. The 3CRR, 6CE, 6C* and 7CRS have been gathered from the web site provided by Willott et al. (2003)[5]. The *K*-band magnitudes

[5] http://www.astro.physics.ox.ac.uk/ cjw/kz/kz.html

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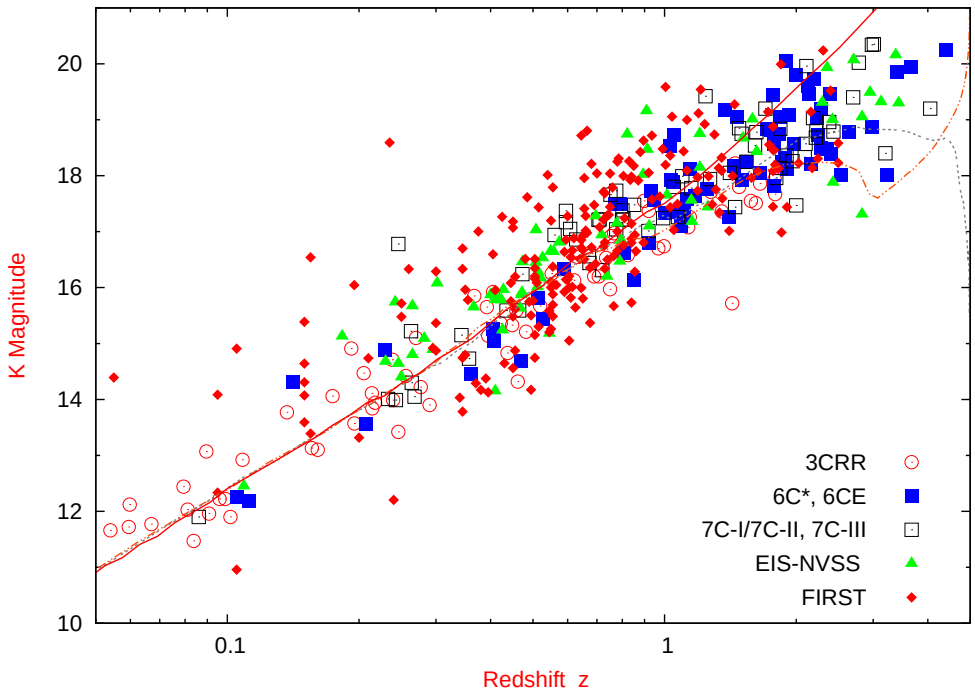

Fig. 3 The $K-z$ Hubble diagram for radio galaxies for the 3CRR, 6CE, 6C*, 7CI/7CII, 7CIII, EIS-NVSS and NDWFS-FIRST-FLAMEX samples. Over-plotted are: a non evolution curve (red colour), instantaneous starburst (black colour) (0.1 Gyr) beginning at $z = 5$ (orange colour) and a starburst lasting 1 Gyr and starting at $z = 5$ (Jarvis et al. (2001)).

Table 1 Different fits to the $K-z$ relation for different samples

Sample	Flux limit	Frequency	Best fit to $K-z$	References
3CRR	10.9 Jy	178 MHz		
6C	2.0 Jy	151 MHz	$K(z) = 17.37 + 4.53\ \log_{10} z - 0.31(\log_{10} z)^2$	Willott et al. (2003)
7CRS	0.5 Jy	151 MHz		
NVSS-EIS	7.2 mJy	1.4 GHz	$K(z) = 17.62 + 4.04\ \log_{10} z - 1.39(\log_{10} z)^2$	Brookes et al. (2006)
FIRST-Boötes	1.0 mJy	1.4 GHz	$K(z) = 17.90 + 4.30\ \log_{10} z$	EL Bouchefry & Cress 2007
FIRST-Boötes/Cetus	1.0 mJy	1.4 GHz	$K(z) = 17.50 + 4.13\ \log_{10} z - 0.30(\log_{10} z)^2$	This work
	—	874 MHz	$K(z) = 17.75 + 3.64\ \log_{10} z$ at all redshift	Bryant et al. (2009)
MRCR-SUMSS	—	874 MHz	$K(z) = 17.76 + 3.45\ \log_{10} z$ at $z > 0.6$	Bryant et al. (2009)
	—	874 MHz	$K(z) = 17.89 + 3.11\ \log_{10} z$ at $z > 1$	Bryant et al. (2009)

and the corresponding redshift for the EIS-NVSS sample have been compiled from the work of Brookes et al. (2006). All magnitudes are on the same metric system (64 kpc) except the FIRST-Boötes sample (2″ aperture). The majority of the FIRST radio sources tend to be fainter than the other samples, this can be clearly seen in Figure 4 which shows the difference between the FIRST-Boötes/Cetus sample and the best fitting $K-z$ relation of Willott et al. (2003). This figure shows that the FIRST radio sources are fainter than the combined sample 3CRR, 6C, 7CRS over all redshifts, and things slightly change at redshifts greater than ~ 2. Brookes et al. (2006) found similar effects in their comparison of the EIS-NVSS sample to the best fitting $K-z$ relation of Willott et al. (2003). Brookes et al. (2006) explained that at these redshifts ($z > 2$) there are no 3CRR sources and the best fit to the $K-z$ relation is a fit to the 6C and 7CRS samples alone (see their figure 3b). However, the small fraction of the sources identified in K band and the absence of spectroscopic information does not allow more conclusions.

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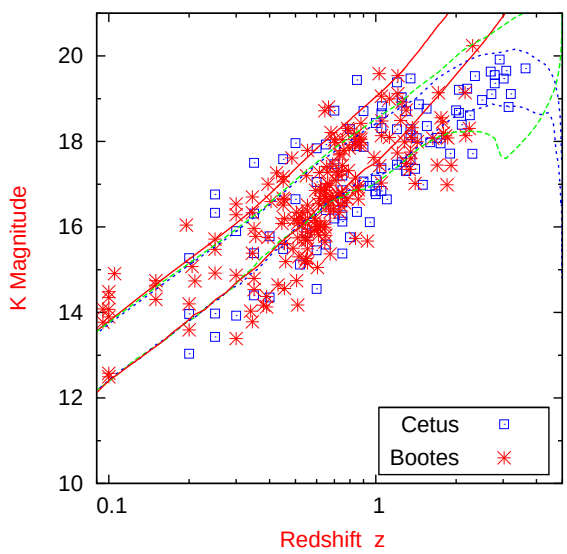

Fig. 2 The $K-z$ Hubble diagram for all FIRST radio sources identified in Boötes and Cetus fields. The three upper curves show: a non evolution curve (red colour), instantaneous starburst (0.1 Gyr) beginning at $z=5$ (blue colour) and a starburst (green colour) lasting 1 Gyr and starting at $z=5$ (Jarvis et al. 2001). The three lower curves are: non evolving galaxies with luminosity 1 $L_\star$ (red curve), the blue and green curves correspond to a passive evolution for galaxies with 1 $L_\star$ assuming all stars in the galaxies formed at $z=5$ and $z=10$ respectively.

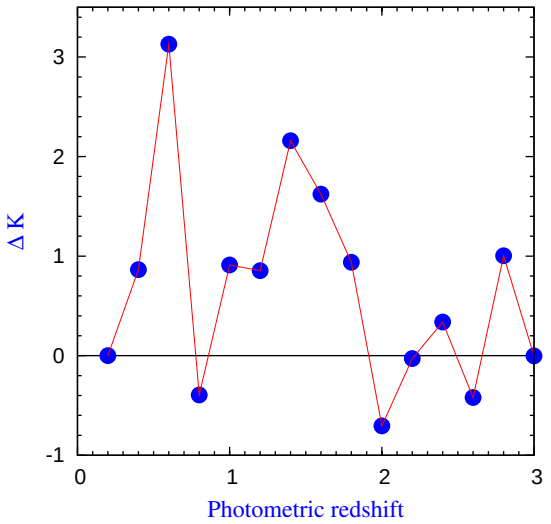

Fig. 4 The offset, ΔK, of the FIRST radio sources compared to the best fitting $K-z$ relation for radio galaxies from Willott et al. (2003). Here $\Delta K = K - K_{fit}$. The data are plotted in steps of $\Delta z = 0.2$.

4 Conclusions

In this paper, the $K-z$ diagram of the faint radio population detected at 1.4 GHz to a limiting flux density of 1 mJy has been investigated. The FIRST radio sources found to follow a similar $K-z$ relation to brighter radio samples, with evidence for a slight offset to fainter K magnitude, consistent with the idea that faint radio survey include fainter galaxies that are different from the typical galaxies associated with bright radio sources. However, One should be aware of the limitation of the NDWFS data compared to the study of Willott et al. (2003). Willott et al. (2003) have obtained complete K band data of the complete radio samples, while only a fraction of radio sources identified in the K band in this study (due to the incompleteness of the NDWFS). Moreover, including only sources identified in several filter with the additional criterion of $\chi^2 < 2.7$ (accurate photometric redshift) make the sample more incomplete. These conclusions should be taken on the understanding that a high spectroscopic completness, deep K band data in the NDWFS survey, is required before one can draw any conclusions. But, it is encouraging that the K band magnitudes with photometric redshift agree with the Willott et al. (2003) relation.

This paper also presented a composite $K-z$ diagram of FIRST radio sources and low-frequency selected radio samples with progressively fainter flux-density limits: 3CRR, 6CE, 7CRS and the EIS-NVSS. The majority of the FIRST radio population tends to lie at fainter magnitudes possibly indicating that the galaxy luminosity is correlated with radio power (Willott et al. 2003, Mclure et al. 2004).

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